# Electrical Power Generation From Electrostrictive Polymers for Autonomous Distributed Systems

Dr. George W. Taylor
Ocean Power Technologies, Inc.
1590 Reed Road
West Trenton, NJ 08628
Telephone: 609-730-0400
Fax: 609-730-0404
e-mail: oceanpwr@aol.com
Award# N00014-98-C-0274

## LONG-TERM GOALS

There is an ever-growing military, scientific and commercial need to establish Autonomous Distributed Systems (ADS) for studying and measuring oceanographic, atmospheric and other data in the littoral regions of the world. The long-term goal of this program is to develop an electrical power supply for these applications, that is reliable and easy to operate, has a long maintenance-free operating life, and is as low cost as possible. An ideal system for meeting these goals is to have a power generation system that directly converts the mechanical energy in waves and currents into electricity. This electrical energy, scavenged from the ocean environment, can then be used to directly power or to recharge the batteries of the components in the ADS.

The successful completion of the program will provide remote electric power generating equipment for water based military and civilian applications having capacities of a few watts to hundreds of kW. Based on unique piezoelectric and electrostrictive polymers, the generators require no fuel and produce no emissions. Battery recharging stations for autonomous underwater vehicles and undersea sensor networks will have their mission duration capability extended for years. Long lived oceanographic data collection systems will be possible for weather prediction and environmental monitoring.

## OBJECTIVES

The program will focus in detail on electrostrictive device fabrication techniques for high reliability operation under large mechanical stress in high voltage, high power electronic circuits. It is expected that the electrostrictive polyurethane generator will have low mechanical and electrical losses and that this will result in the electrostrictive generator having a mechanical to electrical energy conversion efficiency in the range 50% to 75%, i.e., two to three times greater than that presently achievable with a piezoelectric PVDF generator. The new electrostrictive generator is expected to be physically smaller and less expensive to manufacture.

The Program’s technical objectives will be to continue polymer materials development, demonstrate the power capabilities of the selected polymers and power conversion electronics, and demonstrate a complete generator in laboratory operation:

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- Demonstrate an at least two fold performance gain of polyurethane electrostrictive polymers, operated as electric field induced piezoelectrics, over PVDF in an OPT AUV recharging generator operating in the laboratory.

- Work will be continued in parallel to develop electric field induced piezoelectric PVDF:TrFE as a higher performance replacement for polyurethane. It is an extremely new material and requires significant fabrication process development as well as performance characterization. If the material continues to exhibit its outstanding behavior and can be produced in sufficient quantity, OPT will demonstrate an at least three fold performance gain of PVDF:TrFE over PVDF in an AUV recharging generator operating in the laboratory.

The Phase II Option's technical objective will be to demonstrate an OPT AUV laboratory generator operating in a mission power profile selected by the Navy Program Manager.

**APPROACH**

Ocean Power Technologies, Inc. (OPT), expert in ocean power extraction, and the Materials Research Laboratory (MRL) of Pennsylvania State University, expert in piezoelectric materials, have teamed in this program to investigate the use of the electrostrictive polymer polyurethane (PU) and PVDF:TrFE copolymer as a superior alternative to commercial piezoelectric PVDF for use in OPT's wave power generation systems.

The proposed program is planned to flow from development and demonstration of the technology for each component of an OPT generator to the demonstration of a fully functional generator operating in the electrical load profile of a Navy selected AUV application.

The OPT and Pennsylvania State University's Materials Research Laboratory (MRL) team began the program with a design review of the small laboratory generator test section concept that was developed in Phase I.

OPT has fabricated the small test generator mechanical structure and is reviewing the design of the power conversion electronics. MRL has fabricated several polyurethane polymer elements required for testing. OPT has also found a commercial vendor of polyurethane and will also test the quality of these samples. Measurement Specialties, Inc. (MSI) has been utilized to provide polymer electroding services with carbon based materials and the electrical connection system, that can withstand high strain levels. The test unit was assembled and put into operation at OPT.

The small test generator system has been operated through a range of frequencies and strains. Further tests will be done to decrease DC leakage through the material and further characterize the relationship with frequency in the material. The first generating elements are single layer polyurethane in order to correlate the results with those obtained in the Phase I Option. PVDF:TrFE elements will evaluated to allow a choice to be made as to the best overall material for this application. Then multi-layer elements will be used. They will have higher capacitance which is preferable for the switched resonant circuit operation. The multi-layer elements will provide the opportunity to address issues that arise from higher power output levels, electrical lead attachment, heat transfer, and reliability. A key result of this testing will be quantifying the amount of electrical and mechanical losses in the material. The tests will be conducted at OPT, and will use OPT's resonant electronics approach as well as matched resistive loads. Based on the results, a larger generating system will be designed and fabricated. The laboratory prototype generator will be tested and demonstrated for a 3 month period, and its performance and reliability recorded. Problems will be addressed immediately to obtain the best performance.

## WORK COMPLETED

OPT has continued its work on voltage/bias/d31 as well as the addition of measurements pertaining to the force required to strain the material. These force measurements have been used to verify the Young's Modulus of the material.

OPT has completed the assembly and debugging of its new small laboratory test generator. The higher operating frequency of the generator, up to 14 Hz, allows for the ongoing characterization of the polyurethane. The generator has been designed to operate at 2,4,6,8 and 10% strain.

Tests were conducted on polyurethane through the range of higher operating frequencies with constant sinusoidal strain amplitude of 9.4%. OPT has plotted a very linear behavior between the output voltage and frequency as expected, but discovered that the slope is slightly shallower than needed to maintain a constant value of d31 with frequency.

## RESULTS

The summary conclusions of work performed to date are:

The consensus of MRL and MSI is that the non-linear material behavior was explainable, and offered a couple of different possibilities, namely the Maxwell Stress effect, and a new proportionality to define d31. The first is currently being investigated to see if the difference is of the same magnitude as those measured, and the latter is being reviewed as an explanation. OPT has run into a problem with current leakage through the Polyurethane due to the Bias Voltage, and MRL has suggested that other soft polymers have similar Young's Modulus and d31, while exhibiting much lower levels of leakage through the material. They are currently exploring these alternative materials.

It is shown that values of d31 fall off nearly 8% over a frequency range of 2 through 11 Hz demonstrating that polyurethane exhibits a frequency dependence on d31 favoring low frequency stretching. The frequency dependence is found to relate to the "softness" of the polyurethane, as the Young's Modulus also tails off with frequency. During high frequency stretching the expected constant values of d31 and Y become a function of the material interactions on a molecular level, rather than characteristics of the structure.

## IMPACT/APPLICATIONS

Upon successful completion of this program, OPT will be positioned to sell its electric power generating equipment for water-based government and private sector applications having capacities of a few watts to many kilowatts. That breadth of power capacity, coupled with the following key advantages of OPT's power system, presents a significant opportunity:

- The “solid state” nature of the electrostrictive materials is highly resistant to salt-air and other corrosive effects, and can withstand a wide range of temperature.
- The generators require no fuel and produce no emissions.
- Significantly higher duty cycle than wind and solar (photovoltaic).
- OPT’s systems will operate at high efficiency, with small size, and are efficient at low and variable speed.
- If the technical goals of the Program are achieved, OPT estimates that electrical power for small, secondary power applications (1 watt to 1 kilowatt) will be in the range of 7¢ - 10¢ per kilowatt hour, including capital and operating and maintenance costs. This compares very favorably to diesel power (25¢ - 100¢ per kWh, depending on location), solar/photovoltaic power (25¢ - 75¢ per kWh), and wind power (10¢ - 30¢ per kWh).

The successful development of generators utilizing electric field induced piezoelectric polymers has important applications including the following:

(a) For overt surface deployed and covert sub-surface deployed power generation:
- Tether points for local recharging of underwater equipment such as AUV’s for application within the Autonomous Oceanographic Sampling Network.
- Visual, radio, radar interactive channel markers for follow-up landings where harbor infrastructure facilities are unavailable or destroyed.
- Long-live hydrophone arrays or other data acquisition sensors, including undersea sensor networks, sonar buoys and weather reporting buoys.
- Power for coastal defense networks, islands or remote coastal locations.

(b) For high current flow situations, the generator can be re-configured to generate power under the surface for similar functions as above.

(c) 10 to 200 watts generators for powering lights and horns for aids to navigation for the U.S. Coast Guard.

(d) Power for oceanographic research sensor and data communication.

(e) Power for aquaculture (fish farming) installations.

**TRANSITIONS**

MRL is the leading research institute in the U.S. on piezoelectric and electrostrictive materials. This research covers single crystals, ceramics, thin films and polymers. Significant in terms of related work to this program is that MRL is investigating the properties of the electrostrictive polyurethane for use in actuators, i.e., the reciprocal application to generators.

**RELATED PROJECTS**

Under its current development program, OPT has worked on the construction of prototype power generating systems based on both electromagnetic technology and the piezoelectric polymer PVDF. OPT has also had (i) a Phase I SBIR Contract from Office of Naval Research to investigate the feasibility of an OPT Generator located either at or below the surface to provide up to 1 kW of power to recharge the batteries of Autonomous Underwater Vehicles; (ii) OPT has received the Phase II contract for the AUV program to deploy and test a 1 kW surface system in the ocean; (iii) OPT, with Princeton University, Pennsylvania State University and Autonomous Underwater Systems, Inc., is working on a contract for the generation of electrical power from the flow energy of water (rather than ocean waves), using eel-like generating system structures made from piezoelectric polymers.